

**International Energy Agency Task 5**

**4<sup>th</sup> Specialists Meeting on Component Failure Rate Data**

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# **Statistical analysis of JET Operation Reliability**

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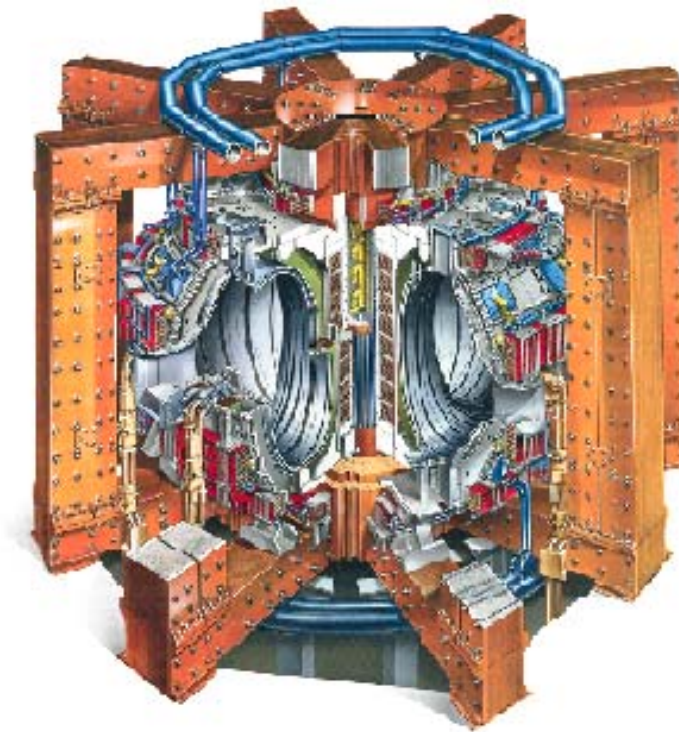
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# Outline

1. JET Tokamak
2. Organisation
3. Experimental Campaigns
4. Optimisation of JET Operation
5. Technical Indicators
6. Statistical Analysis : principles, practical examples
7. Overall summary

# 1. JET Tokamak



## **JET is a tokamak with :**

Torus radius	3.1 m
Vacuum vessel	3.96 m (h) x 2.4 m (w)
Plasma volume	80 m <sup>3</sup> - 100 m <sup>3</sup>
Plasma current	5 MA
Main confining field	up to 4 Teslas

JET is currently the largest tokamak in the world. It is the most close machine to ITER. Numerous scientific and technical experiments are carried out every year on this machine in preparation of ITER.

## 2. Organisation

**Operator :** - **UKAEA** (operation and maintenance of the machine)

**Users :** - **Associations (European Laboratories)**  
proposition & execution of experimental campaigns  
- **Collaborators under International agreements**

**Monitoring :** - **EFDA-JET Close Support Unit (CSU)** on behalf of the **EC**.  
EFDA-JET Associate Leader and Head of CSU: J. Pamela  
**Operation Dpt :** monitors JET Operation carried out by the Operator and JET Fusion Technology Activities carried out by the Associations.  
**Programme Dpt :** defines and monitors experimental campaigns in collaboration with the Associations.  
**Enhancement Dpt :** monitors the preparation & installation of JET enhancements designed by the Associations.  
**Administration Dpt :** Finance and resources

### **3. Experimental Campaigns**

#### **Annual workprogramme**

- Experimental campaigns (intensive operation: ~130 days / year; 2 sessions / day)
- Maintenance breaks
- Shutdown & restart

#### **Campaign:**

- Duration: 10 to 30 experiment days
- Sessions: 2 / day

#### **Session**

- Targeted pulses: ~12.5 / session (25 / day)
- Technical / Physics supervisor: Session Leader

#### **Pulse** (production of plasma)

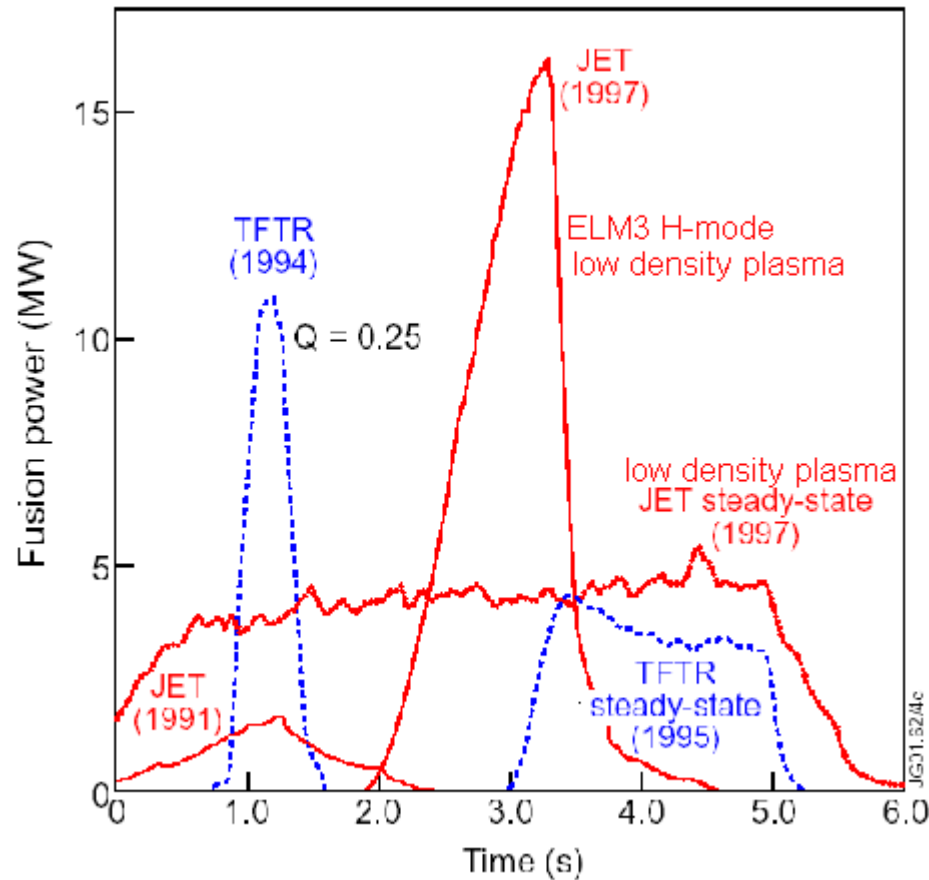
- Interpulse time: 30 mn (coils cooling, heating scenarios set-up, data acquisition, ...)
- Duration: few seconds to few tenths of seconds

Each campaign is focused on a limited number of topics.

Year	Campaign	Main Topic
2000	C1	Consolidation of Physics Basis for ITER : <i>Plasma shaping ; operation near boundaries (confinement, density) ; Effect of Neoclassical Tearing Modes ; etc.</i>
	C2	
	C3	
2001	C4	Septum assessment + pure Helium experiments
2002	C5	Septum assessment
	C6	Exploration new quasi-vertical pellet injector
2003	C7	Preparation high performances campaigns (confinement, density, power)
	C8	
	C9	Reverse Magnetic Field
	C10	<b>High Performance</b>
	C11	Trace Tritium Experiments
	C12	<b>High Performance</b>

**High Performance Campaigns push Auxiliary Heating Systems at the limits of their possibilities. For these campaigns, we have accepted the risk of higher failure rate.**

## Evolution of operating scenarios



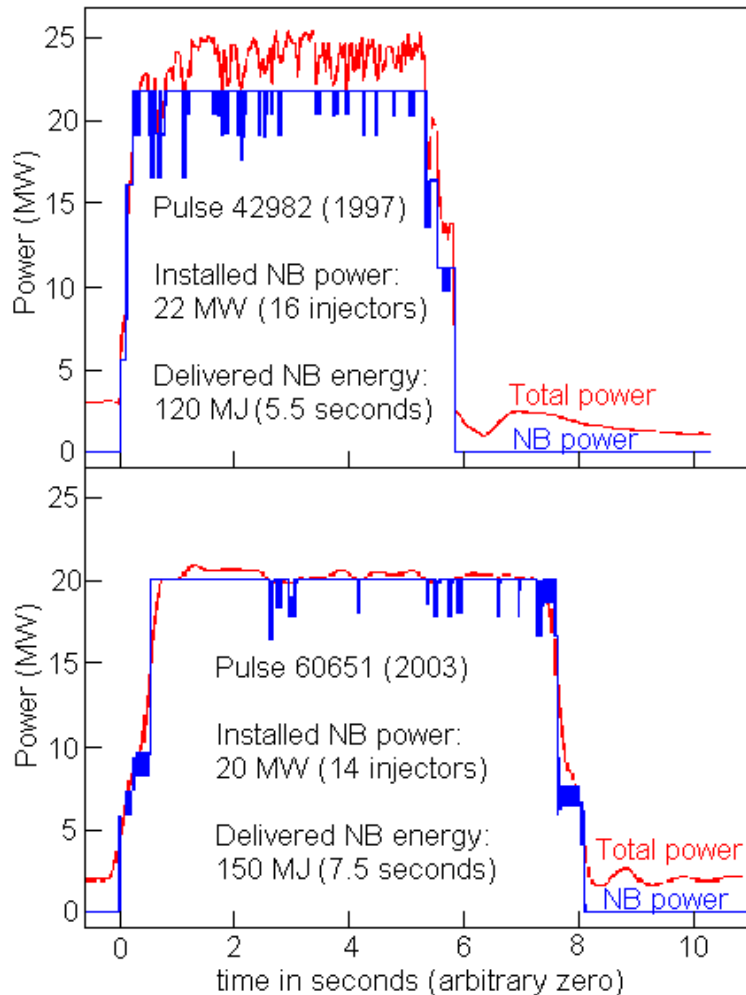
**JET 1991 : 1.7 MW**  
First controlled DT fusion experiment

**TFTR 1994 : 11.5 MW peak**

**JET 1997 : 16 MW peak**  
Energy amplif.  $Q \sim 0.65$

**JET 1997 : 4.5 MW steady state**  
Energy amplif.  $Q \sim 0.2$

# High power long pulse operation is very demanding



Reference scenario for ITER: Steady State ELMy H-mode  
⇒ High density steady state plasma with low collisionality.

The collisionality increases with the density.

**A strong heating is the only way to reduce the collisionality.**

We want to produce steady state plasma with high heating power => we need high heating energy.

The nominal JET NB systems comprise 16 injectors.  
Four 30A injectors have been removed in 2002 for upgrades.

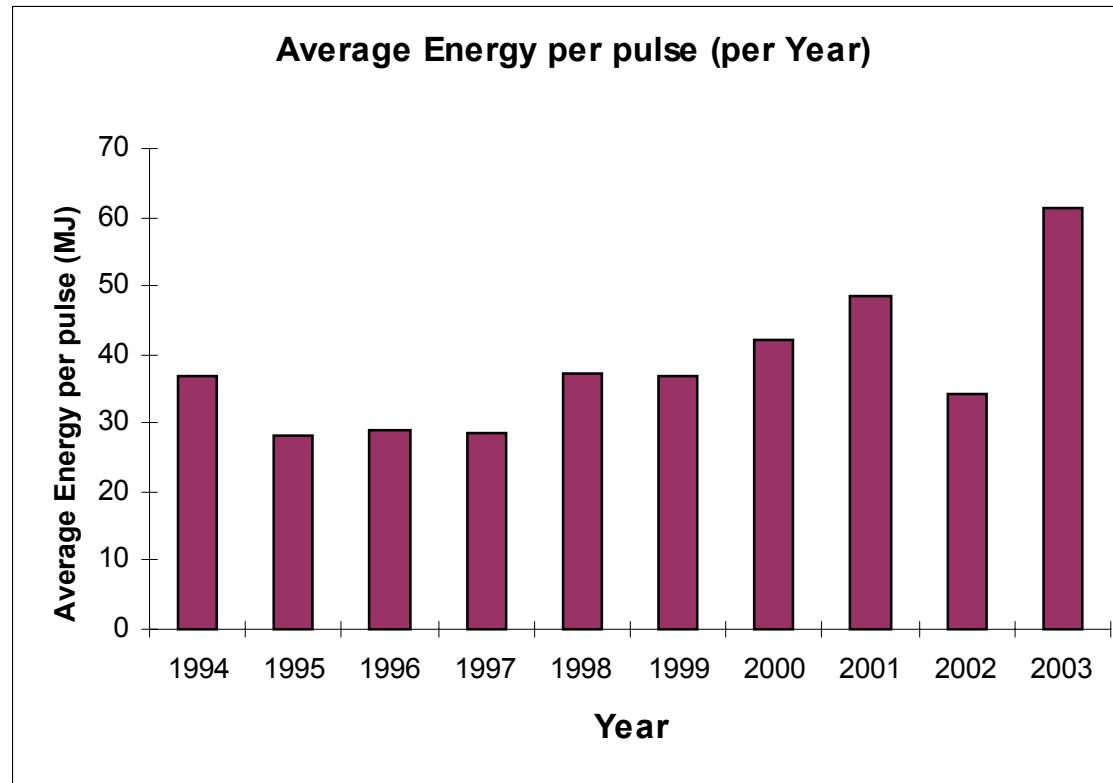
Two new 60A injectors have been commissioned mid 2003.  
⇒ the total installed NB power is now 20 MW.

Two new 60A injectors will be commissioned end 2003.  
⇒ the total installed NB power will be 23 MW.

**High performance experiments always request the maximum available power.**



## Average Neutral Beam Energy per pulse



<b>1994 - 1999 :</b>	<b>16 NB injectors</b>
<b>2002 :</b>	<b>12 NB injectors</b> (4 injector upgrades in progress)
<b>2003 :</b>	<b>14 NB injectors</b> (2 injector upgrades in progress)

## 4. Optimisation of JET Operation

Aim : **to improve the % and number of « Good Physics » pulses per campaign.**

The improvement of JET operation requires an **iterative process** :

Action	When	What is important ?
Definition of work programme	1 year in advance	<ul style="list-style-type: none"> <li>- Content &amp; duration of the campaigns</li> <li>- Maintenance breaks</li> <li>- Contingencies</li> </ul>
Maintenance and upgrades	Shutdown & Maintenance breaks	<ul style="list-style-type: none"> <li>- Prioritization of maintenance</li> </ul>
Commissioning	Restart	<ul style="list-style-type: none"> <li>- Restart targets for each system</li> </ul>
Execution of the Campaign	Campaign	<ul style="list-style-type: none"> <li>- Strategy against faults during sessions</li> <li>- Availability of Systems Responsible Officers</li> </ul>
Record / processing scientific data	Campaign	<ul style="list-style-type: none"> <li>- Diagnostics, data acquisition, computing</li> </ul>
Record of technical Indicators	Campaign	<ul style="list-style-type: none"> <li>- Choice of indicators; method of record</li> </ul>
Post-processing of technical indicators	End of Campaign	<ul style="list-style-type: none"> <li>- Global figures to evaluate campaigns ;</li> <li>- Correlations to identify causes of problems</li> </ul>
Corrective actions	Next shutdown, next campaign	<ul style="list-style-type: none"> <li>- Identification of the roots of the problems</li> <li>- Prioritization of the corrective actions</li> </ul>

## 5. Technical Indicators

### 5.1 Overall Technical Indicators

Annual WP	Shutdowns Maint. breaks Restarts					
	Campaigns	Days Sessions				
		Targeted Pulses	Lost p. (delays)			
			Attempted pulses	Failed p. Aborted p. NSB p.		
				Successful p.	Dry pulses Recovery pulses	
					Pulses dedicated to Physics	Less satisfactory
						Good Physics

**Records for each item : date, number of occurrence, references of detailed documents or reports, ...**

WP : Work Programme

Attempted pulses: 1 increment in pulse counter

NSB : Non-Sustainable Breakdown

Good Physics pulse: pulse useful for physics

## 5.2 Detailed technical Indicators

Issue	Impact on operation	Fault fixed during Interpulse time ?	Consequence	Technical Indicator
Fault	Minor			
	Major	Yes		
		No	Pulse delayed	<i>delay</i>
			Pulse launched with some restriction	<i>fault</i>

**Minor** issue : do not prevent Good Physics pulses

**Major** issue : could prevent Good Physics pulses

**Faults and Delays impacting the operation** are recorded together with the name of the faulty system and sub-system. A detailed fault report is produced.

The Session Leader must decide whether a fault should be more investigated with the aim to fix it (=> next pulse delayed), or the next pulse should be launched (with some restriction on the faulty system during the next pulse).

The causes of **faults** and **delays** are classified according to a general breakdown including the JET facilities and other possible causes (human, procedures, national electricity grid, etc.)

Systems or factors	Sub-Systems or sub-factor
AGHS – Active Gas Handling System	
CISS – Central Interlock & Safety system	4 main sub-systems
CODAS – Control and Data Acquisition System	16 main sub-systems
Cryogenics systems (helium, nitrogen)	3 main sub-systems + cryogenics plant
Cooling systems (freon, water)	6 main sub-systems
Diagnostics	All diagnostics + central acquisition & trigger system
Heating and Fuelling Systems	6 main sub-systems
Human	7 main causes of human error
Machine Instrumentation and Protection system	2 main sub-systems
National Electricity Grid	National Grid Inhibits
PPCC – Plasma Position & Current Control	3 main sub-systems
Protection Systems	3 main sub-systems
PPS – Pulsed Power Supplies	24 main sub-systems
Site Power Supplies	All site PS
Vacuum and Vessel	8 main sub-systems
Other	4 important systems

## 5.3 Other Technical Indicators

### Performances of Auxiliary Heating and Fuelling Systems

System	Indicator
NBI	<ul style="list-style-type: none"> <li>• Max Power injected</li> </ul>
ICRH	<ul style="list-style-type: none"> <li>• Max Power Coupled</li> </ul>
LHCD	<ul style="list-style-type: none"> <li>• Max Power Coupled</li> </ul>
Pellet Injector	<ul style="list-style-type: none"> <li>• Speed, frequency, size</li> </ul>

### Scarce Resources

Topic	Indicator
Radiation	<ul style="list-style-type: none"> <li>• In-Vessel dose rate</li> <li>• In-Vessel 2.4 MeV &amp; 14 MeV neutron flux</li> </ul>
TF coils fatigue	<ul style="list-style-type: none"> <li>• Field</li> <li>• <math>I^2t</math></li> </ul>
Disruptions	<ul style="list-style-type: none"> <li>• Force &gt;250 Tonnes</li> <li>• Force 250-325 Tonnes</li> <li>• Force &gt;325 Tonnes</li> </ul>
Tritium Consumption	<ul style="list-style-type: none"> <li>• Mass of injected tritium</li> </ul>

## 6. Statistical Analysis

### 6.1. Principles

**For a given year or campaign:**

- Calculation of the **main statistical figures** (% of good physics pulses, etc.); comparison with other campaigns.
- Search for **correlation between** the various types of **pulses which are not fully satisfactory** and the **detailed technical indicators** (faults and delays).
- Identification of the **faults** which have a significant impact on the JET operation.
- Analyse of the **detailed reports** in order to determine the **real causes of the faults**.
- Definition of **corrective actions; prioritisation** (difficulty, duration, cost, benefit) in order to get the **best possible improvement with the available resources**.

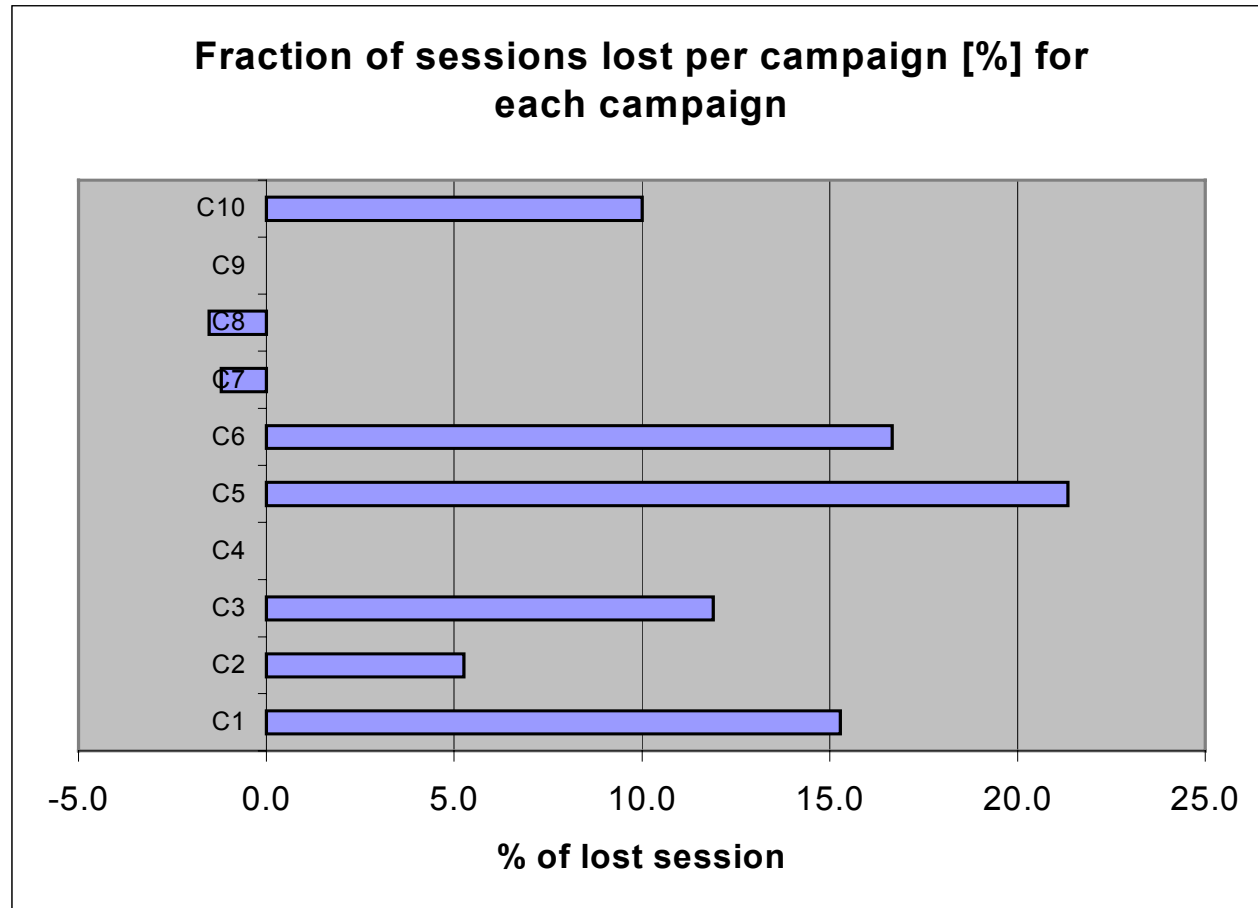
## 6.2. Practical Examples : Campaigns C9 and C10

Campaign	C9	C10
Days of experiments	10	20
Sessions	20	40
Targeted Pulses	250	500
Main Topic	Reverse Field	High Performance
Performances needed from the machine	standard	At the limits of the possibilities of the auxiliary heating systems and their power supplies

For C10, in order to achieve high performance experiments, it was deliberately decided to push the auxiliary heating systems and their power supplies at the limits of their possibilities. The price for this is an increased number of technical faults.



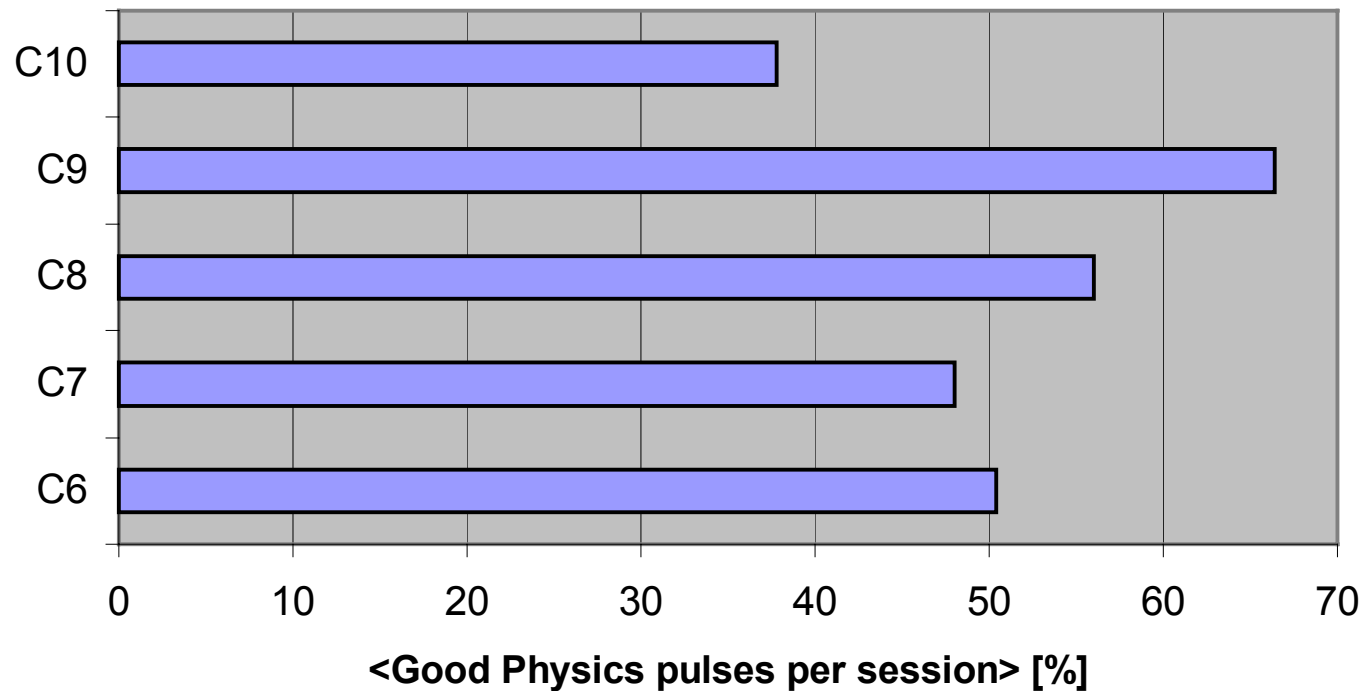
## 6.2.1. Main Figures : comparison between campaigns



**C7 : rearrangement of the campaign**  
**C8 : additional work during week-ends**

**C9 : no session lost**  
**C10: 10% sessions lost**

### Average fraction of Good Physics pulses per session for the 5 last campaigns

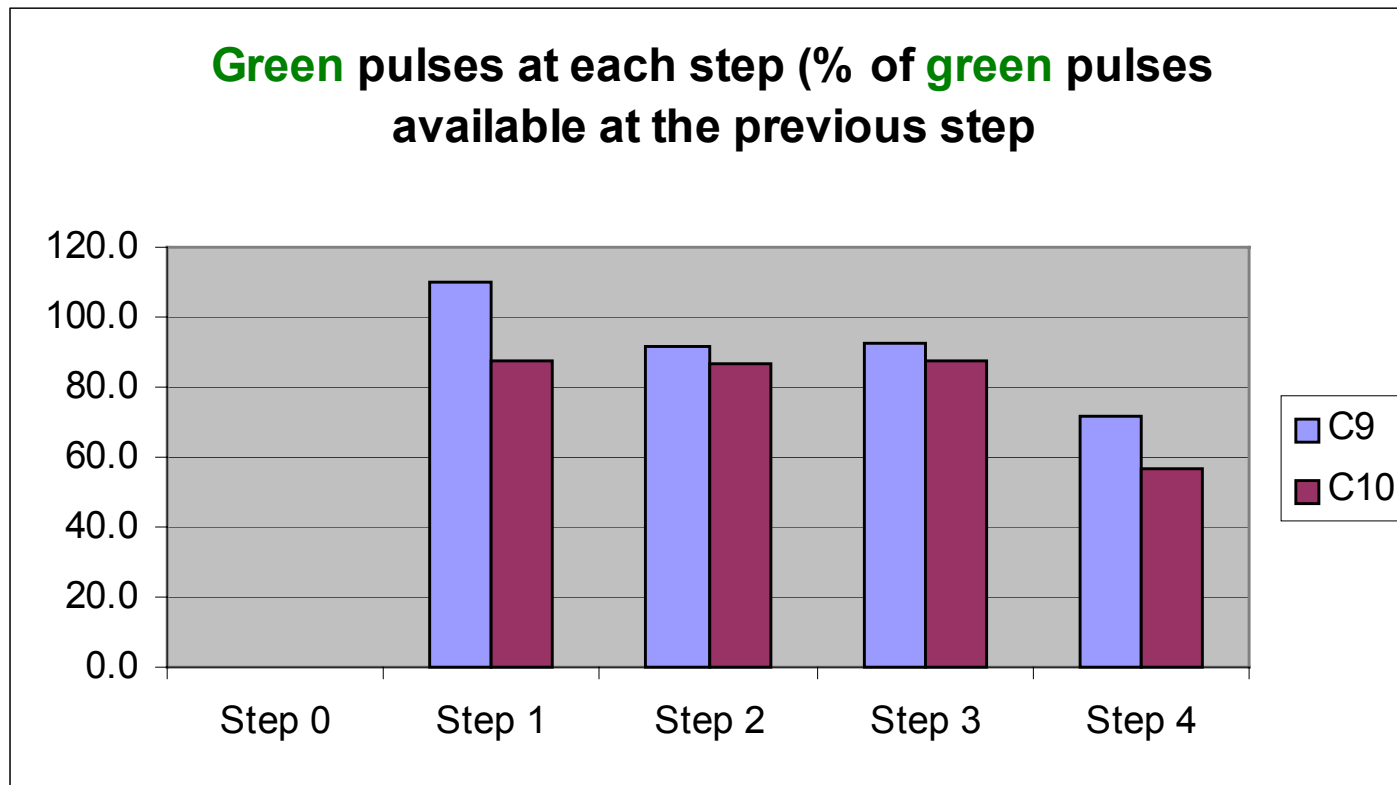


Good Physics pulses are normalised to 12.5 pulses launched per session (i.e. 25 pulses launched per day). This is based on an average interpulse time of 30 mn and on 12h30 experiment time / day.

## 6.2.2. Distribution of pulses during C9 and C10

			Step 1	Step 2	Step 3	Step 4
		Targeted Pulses	Lost pulses (delays)			
			Attempted pulses	Failed p. Aborted p. NSB		
				Successful p.	Dry pulses Recovery pulses	
					P. dedicated to Physics	Less satisfactory Good Physics
C9	"red" pulses	-	-25 (-10%)	24 (9.6%)	19 (7.6%)	66 (26.4%)
	"green" pulses	250	275 (110%)	251 (100.4%)	232 (92.8%)	166 (66.4%)
C10	"red" pulses	-	62 (12.4%)	58 (11.6%)	46 (9.2%)	145 (29%)
	"green" pulses	500	438 (87.6%)	380 (76%)	334 (66.8%)	189 (37.8%)

% refers to the overall number of **targeted pulses**: 25 pulses launched per day. This is based on an average interpulse time of 30 mn and on 12h30 experiment time / day.



Step 0	Step 1	Step 2	Step 3	Step 4
	Lost (delays)	Failed, Aborted, NSB	Dry and Recovery	Less satisfactory
Targeted	attempted	successful	Dedicated to physics	Good physics

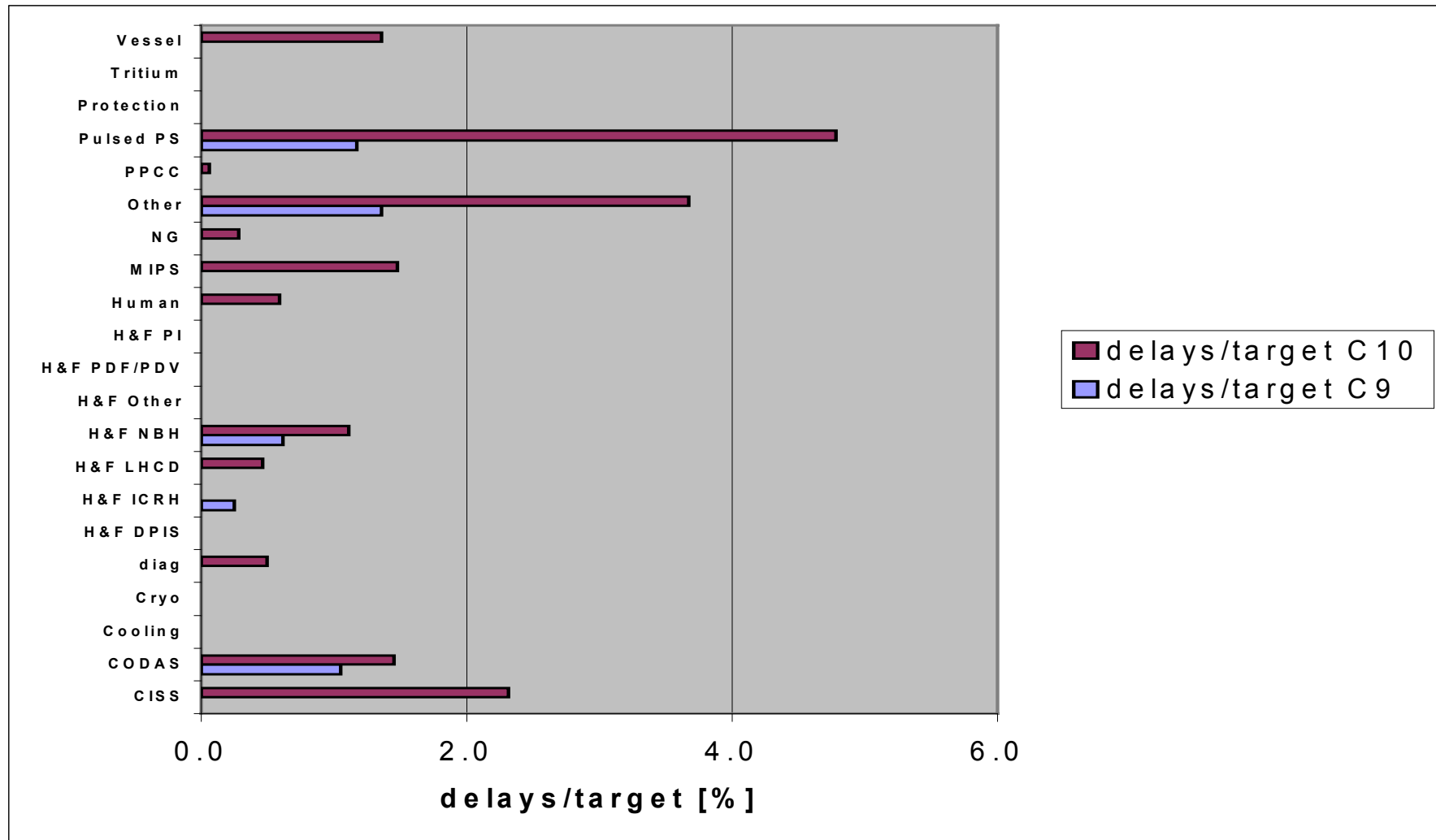
In terms of "green" pulses, the main differences between C9 and C10 are in step 1 and 4.

## Pulses lost at step 1 (delays):

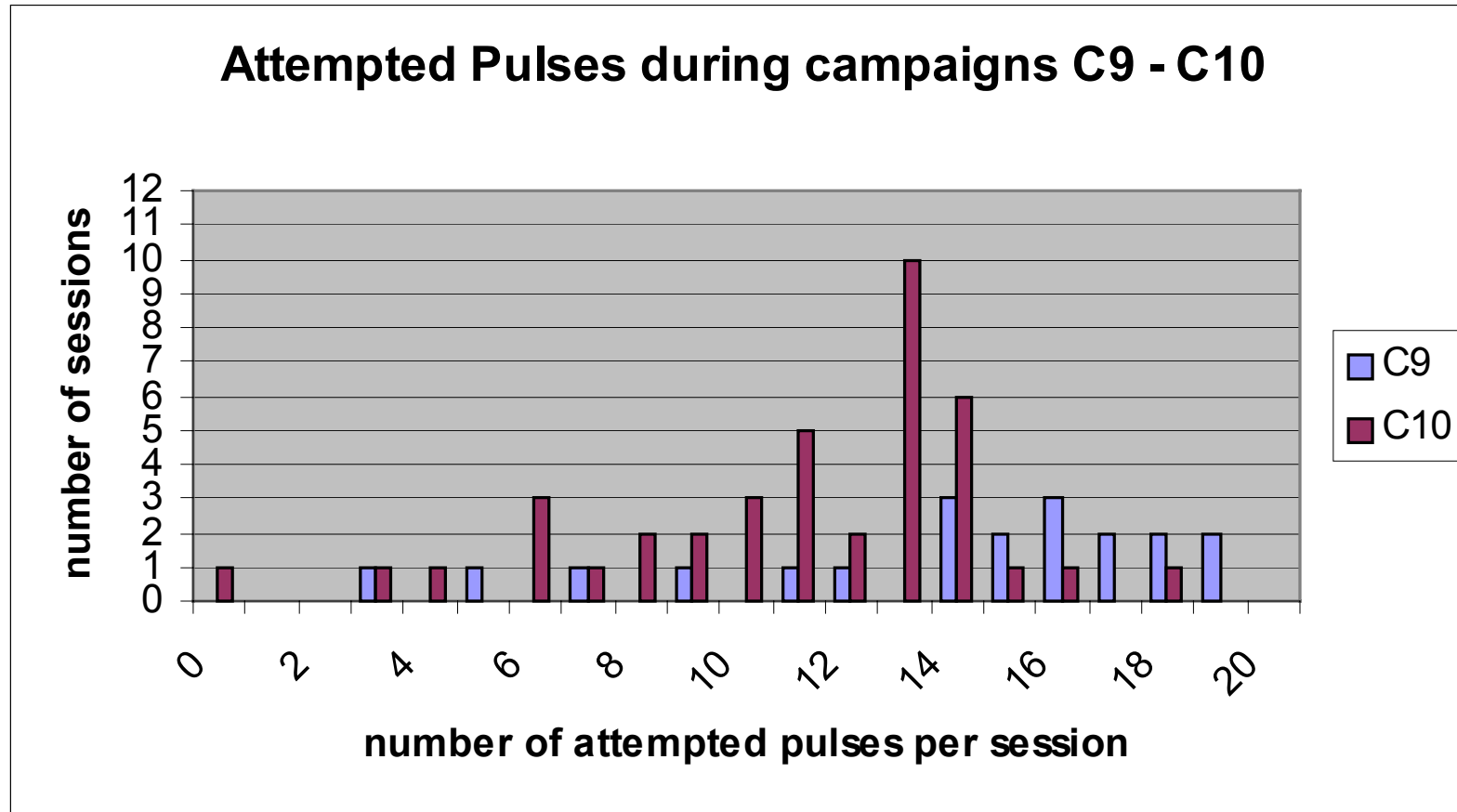
campaign	Time for pulses [hh:mm]	Delay [hh:mm]	Delay [% of time for pulses]	Expected lost pulses (delays) [% targeted pulses]	Actual lost pulses (delays) [% targeted pulses]	Average interpulse time (mn)
C9	125:00	20 :35	16.4%	16.4%	- 10% (gain)	23
C10	250:00	61 :42	24.6%	24.6%	12.4% (loss)	26

- The targeted interpulse time is 30 mn.
- **Owing to interpulse time savings, the actual number of pulses lost at step 1 is lower than expected from delays. For C9, the losses expected from delays are even transformed into gains.**
- **Interpulse time savings are lower for C10 than for C9, because high performance pulses need longer interpulse time than less demanding pulses:**
  - Higher fields => longer time to cool down the coils
  - Complicated heating system scenarios => longer set-up time
  - Complex new physics scenarios; pioneering work => more thinking time needed.

## 6.2.4. Main causes of delays



## Distribution of Pulses by categories for C9 and C10



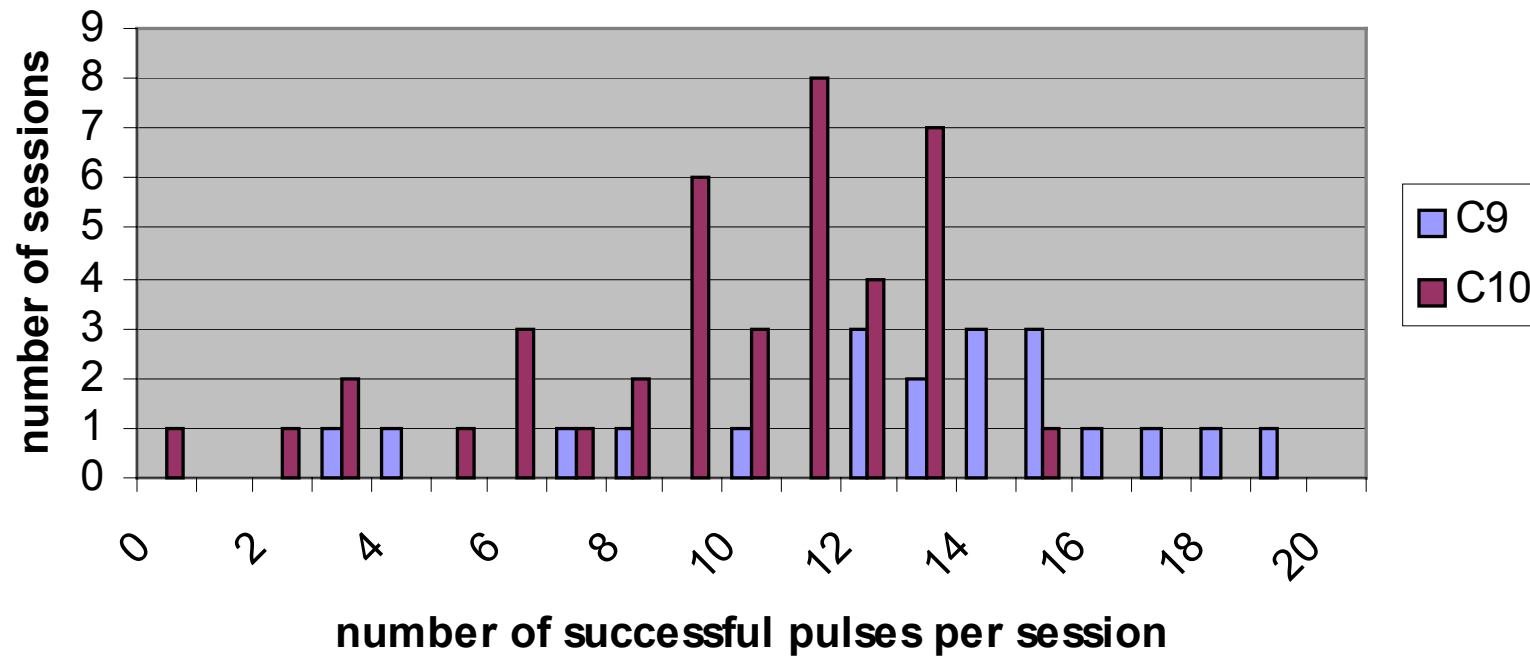
**C9**

- peak at 14 – 16 : very good

**C10**

- peak at 13 : good

## Successful Pulses during campaigns C9 - C10



### C9

- Peak at 12 – 16 : excellent
- Maximum at 19 : excellent

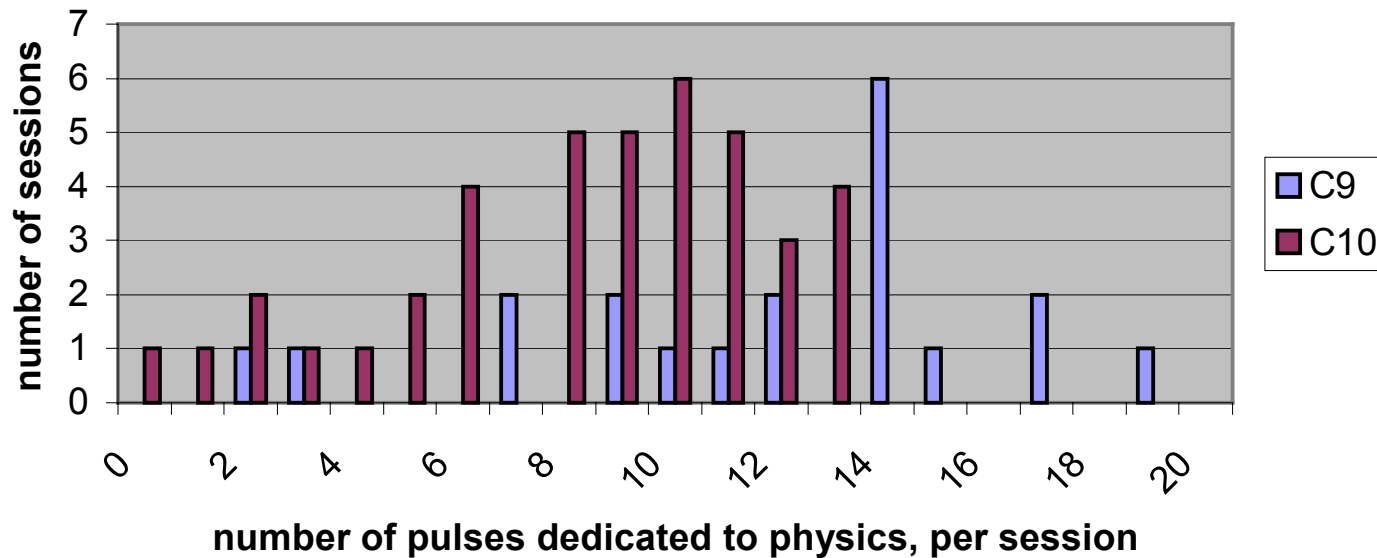
### C10

- Peak at 12 : good
- Maximum at 15: good





## Pulses dedicated to Physics during C9 - C10



### C9

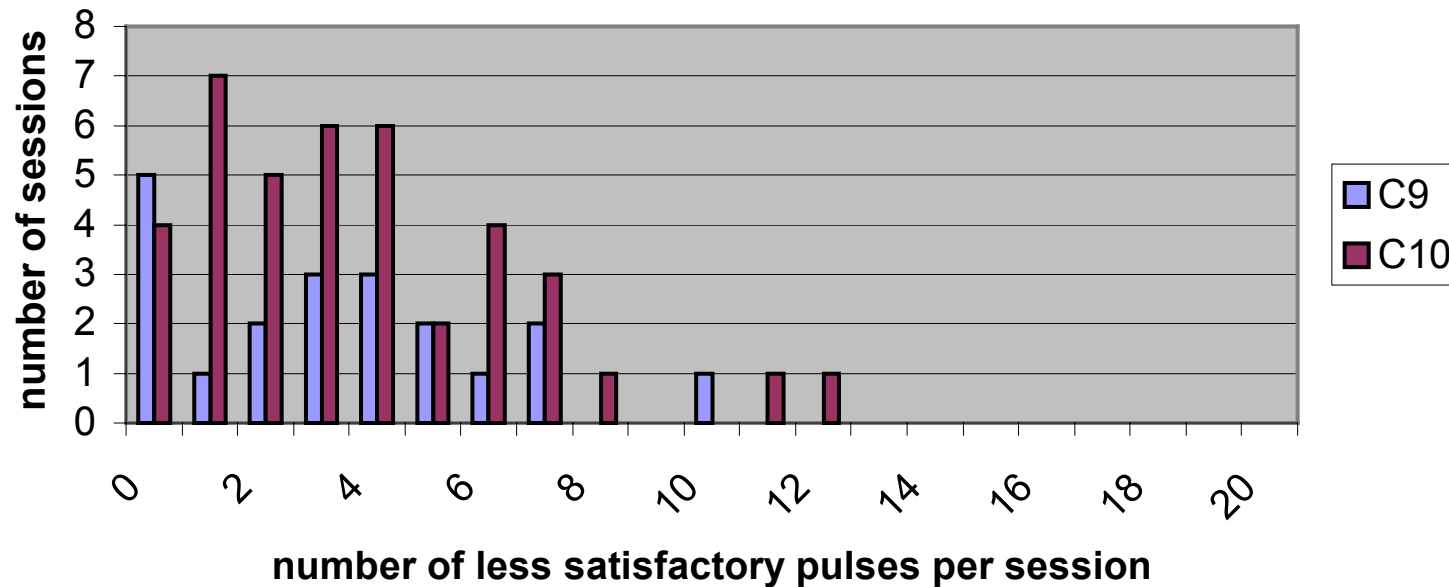
- Peak at 14 : excellent
- 80% of the sessions have more than 2/3 of targeted pulses (>8 pulses) dedicated to physics : very good

### C10

- Peak at 10 : good
- ~ 60% of the sessions have more than 2/3 of targeted pulses (>8 pulses) dedicated to physics: good



## Less satisfactory pulses during campaigns C9 - C10



### C9

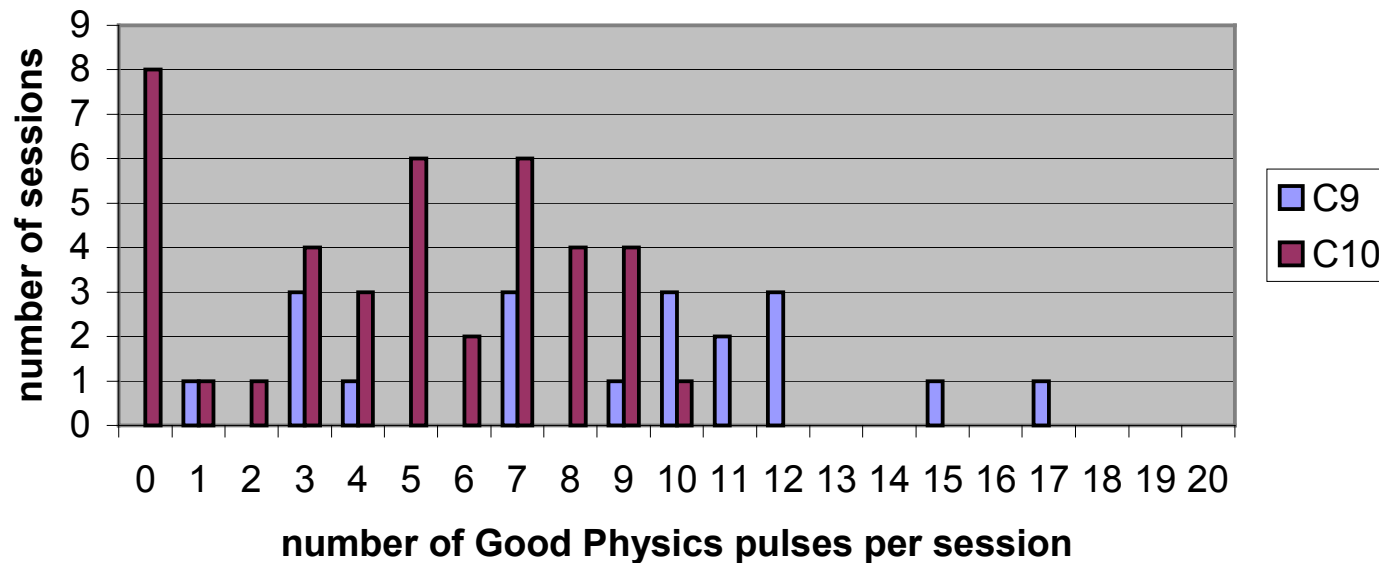
- Peak at 0 : excellent
- Distribution is too broad

### C10

- Peak at 1 : good
- Distribution is too broad



## Good Physics Pulses during campaigns C9 - C10



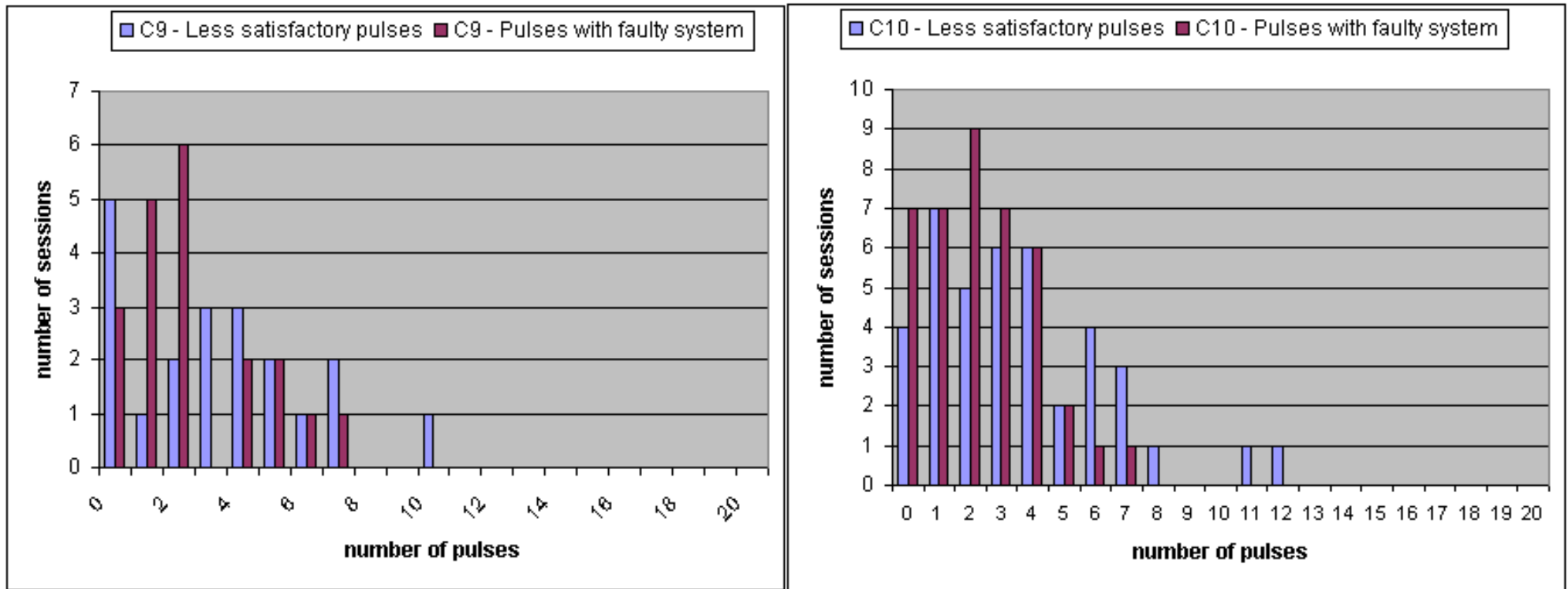
### C9

- Distribution is too broad
- 55% of the sessions have more than 2/3 of targeted pulses (>8 pulses) which gives Good Physics results: good

### C10

- Peak at 0 : 4 fully lost sessions, 4 bad sessions (under investigation)
- Distribution is too broad

## 6.2.3. Less satisfactory pulses

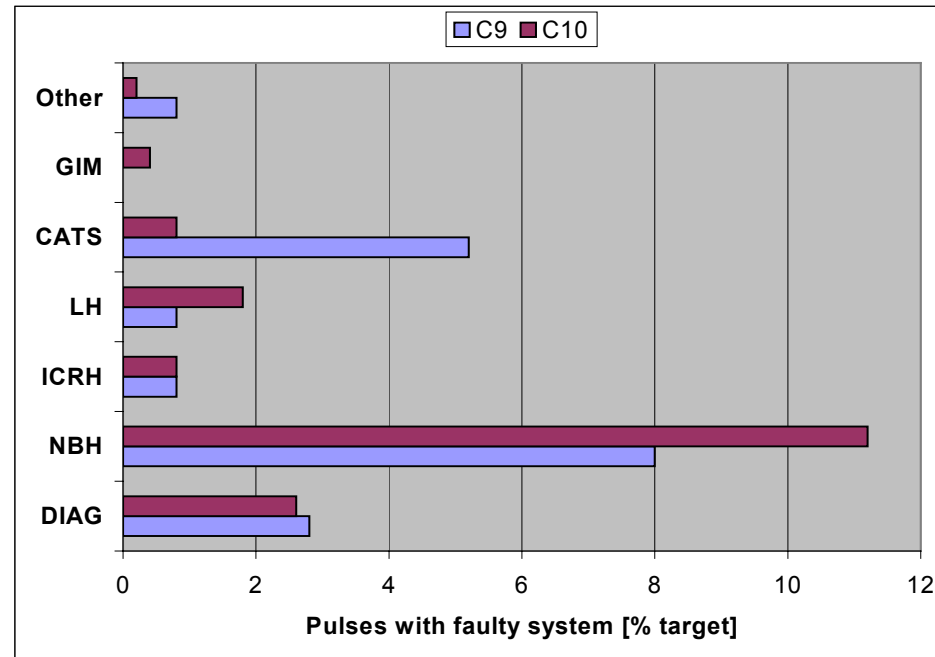


**C9 : No correlation between less satisfactory pulses and pulses with faulty systems<sup>1</sup>**

**C10 : Less satisfactory pulses are correlated with faulty systems (correl. coef. : 89%)**  
**Pulses with faulty systems (94) are not the only cause of less satisfactory pulses (145)**

(1) Auxiliary system or related sub-system totally or partially faulty during the pulse.

# Faulty<sup>1</sup> Auxiliary Systems during C9 and C10



**C9 uses NB systems with some margin that allows fault compensation.**

**C10 high performance experiments need the full installed NB power. No margin exists. Any single unavailability or small reduction may impact the programmed power waveform and hence the pulse rating. This explains the correlation between less satisfactory pulses and pulses with faulty auxiliary systems (especially NB).**

(1) Auxiliary system or related sub-system totally or partially faulty during the pulse.

## 6.2.5. Questions raised by these results (1/2)

### Analyse the campaign plans

- The risk of loosing a session depends on the topic of the campaign. It is higher for high performance campaigns than for standard campaigns. Campaigns include contingency time - **Can this be optimized ?**

### Analyse the way sessions are prepared

- The better the sessions are prepared, the less intershot time is lost
- High performance experiments need more preparation than less demanding ones.
- Interpulse time was saved during both C9 and C10. **Are further savings possible by improving the preparation of sessions?**

## Questions raised by these results (2/2)

### Analyse the way sessions are led

- Analyse lost pulses due to faulty systems: is it possible to optimize the balance between the time (delays) spent during sessions to fix non-intermittent faults and the final number of Good Physics pulses?

### Maintenance strategy

- Are the main problems well identified ? Are the real causes well identified ?
- Is it possible to improve the balance between preventive and corrective maintenance?

(...)

## 7. Overall summary (1/2)

- **Technical indicators** have been developed to give quantitative data on JET operation. These indicators comprise the main criteria of JET operation effectiveness and the main parameters which could influence these criteria. **Statistical analysis** of these indicators provide a **global evaluation the effectiveness of JET operation** and enable to identify **correlations**.
- The criteria to evaluate a campaign must be carefully chosen.
- The search for correlation between effectiveness criteria and possible causes must be carried out in a systematic way.



## Overall summary (2/2)

- JET operation reliability depends on many parameters :
  - The topic of the campaign (reliability decreases when systems pushed to their limits, ...)
  - The plans of the campaign (=> optimisation of contingencies, ...)
  - The way the sessions are prepared (=> saving more interpulse time, ...)
  - The way the sessions are led (balance between delays and less satisfactory pulses, ...)
  - The maintenance strategy (balance between preventive and corrective maintenance, ...)
  - (...)
- Other parameters which also impact the effectiveness of JET operation :
  - National Electricity Grid supply
  - Procedures (safety, administrative, ...)
  - Human (training, staff availability, ...), etc.
- Actions to improve reliability will be formulated on the basis of this analysis and prioritized within the constraints of the available resources.